

VALVE PERFORMANCE AND LIFE OF RECIPROCATING COMPRESSORS

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ABSTRACT

The operation of a reciprocating compressor is

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closely linked to the performance of its valves in terms of life and efficiency. Most operators report that the most significant cause of forced outages of reciprocating compressors is related to valve failures. In designing a reciprocating compressor valve, desirable functional attributes include good sealing, rapid opening and closing, sustained high flow area and low flow resistance, minimum bouncing upon impact, toleration of impact forces and high temperatures, and low flow resistance. Proper design choices, such as material, mass, spring constant, lift, and flow area will maximize the success of the design. However, simple passive valves do not tolerate wide operating ranges well, often suffering from valve leakage at low pressure ratios and reduced valve life at higher pressure ratios.

Valve failures can be divided into two major categories, environmental and mechanical. As impact velocities increase due to higher valve lift or valve operation at off-design conditions, the velocities cause excessive impact stresses and an accelerated damage rate to the valve. Some mechanical causes can be controlled with a good design of the valve components, although the design of a valve is usually optimized for a single design point based on the fixed mass, stiffness, and damping of the design.

To better understand the factors that affect reciprocating compressor valve performance and life, a research program was undertaken to systematically investigate the physical behavior of valve plates during compressor operation. The valve plate life of a reciprocating compressor is generally considered to be a function of the plate's cyclic kinematics, transient stresses, and material properties. Thus, the valve research program aimed to incorporate these fundamental factors into an analysis model that accurately predicts valve life for a given application, geometry, and plate material. The research results benefit users within the gas compression industry by providing a basis for improvements in applications engineering and operational decision-making related to reciprocating compressor valves. The analysis model developed by the research program is based on

results from plate single impact strain gauge tests, dynamic finite element (FE) calculations, optical valve plate 3-D motion measurements, and material high cycle fatigue testing. This paper describes the research program, experimental and analytical results, and the valve life and performance prediction tool that was developed along with recent research findings to advance passive valve technology.

INTRODUCTION

In designing a reciprocating compressor valve, desirable functional attributes include good sealing, rapid opening and closing, sustained high flow area (when open), minimum bouncing upon impact, toleration of impact forces and maximum temperatures, and low flow resistance. Proper design choices, such as material, mass, spring constant, lift, and flow area will maximize the success of the design. However, simple, passive valves do not tolerate wide operating ranges well. The challenge to the current research program is to develop an application tool and technology choices to achieve longer valve life with low loss and acceptable valve operation (including leak potential). Design improvements often come at a price because low flow resistance, which adds to longer life, conversely leads to excessive impact forces. Valve manufacturers have made many advances in materials and configuration. Yet, design trade-offs, parameter selection, and operation of valves are often mismanaged, because application engineering tools are not readily available.

Valve failures can be divided into two major categories, environmental and mechanical (Hoerbiger, HCA 8200-86). Environmental causes are those elements in the valve environment that can lead to valve failure, such as corrosive contaminants, foreign material, liquid slugs, or improper lubrication. Environmental failures can sometimes be prevented by the proper choice of valve material and conditioning of the gas stream (filtration, separation, etc.). Mechanical causes are valve failures that result from high cycle fatigue and abnormal mechanical motion of the valve, caused by high valve lift, valve operation at off-design conditions, valve flutter, pulsations, or spring failure. As impact velocities increase due to higher valve lift or valve operation at off-design conditions, the velocities cause excessive impact stresses and an accelerated damage rate to the valve. Some mechanical causes can be controlled with a good design of the valve components (guard, seat, moving element, and springs), although the design of a valve is usually optimized for a single design point based on the fixed mass, stiffness, and damping of the valve plate and springs.

Perhaps the most common cause of plate or spring failure is valve operation at off-design conditions. In designing a valve to work reliably without failure, a range of operating conditions is assumed. The design, however, is optimized for a single set of operating pressures, temperatures, speed, cylinder clearance, gas molecular weight, lubrication rate, and pulsation level. When the operating conditions significantly deviate from the ideal case, the valve design reliability is not necessarily ensured (Chaykosky, 2002). With the recent increased need for variable speed compressors in the reciprocating compressor market, the off-design operation of valves is more evident and seen by more failures in valves.

The efficiency of a reciprocating compressor also strongly depends on the performance of its suction and discharge valves. In high-speed units (600 RPM or more), valve performance is aggravated further by the increased frequency of valve impacts, higher impact velocities, and reduced flow areas. In general, the ideal compression cycle of a reciprocating compressor is affected directly by valve losses, which lower the adiabatic efficiency of the machine (Gartmann, 1970). Valve performance is critical to both compressor efficiency and reliability. In turn, compressor efficiency has a direct impact on capacity when the driver is operating at its maximum power.

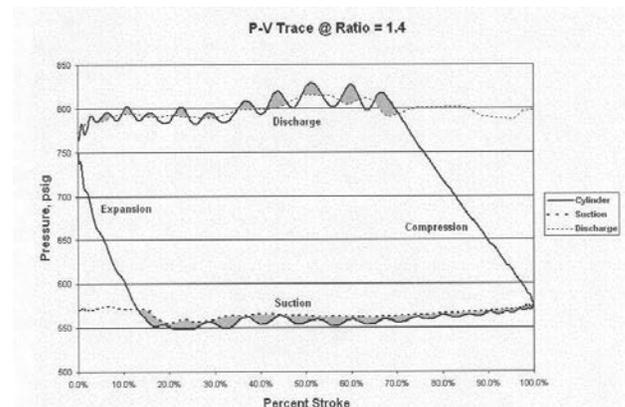


Figure 1: Typical P-V Chart Illustrating Valve Horsepower Losses

Several past studies have been conducted to understand valve failures and prolong valve life in order to improve compressor performance. In a 2003 study, engineers at El Paso Corporation investigated six different compressor valves from five manufacturers in order to determine valve efficiency, reliability, and cost of operation (Noall and Couch, 2003). The six-month investigation found that valve efficiencies were directly related to compressor pressure ratios, where inefficiency was attributed to

valve leakage at low compression ratios (likely due to low stiffness springs or wear in the valve seats over time). This finding highlights the critical problem in operating traditional valves at non-ideal (off-design) operating conditions. In addition, the El Paso study found that the losses through suction valves were approximately twice as great as the discharge valve losses (Noall and Couch, 2003). Figure 1 shows an example of a P-V trace from a typical compressor with a pressure ratio of 1.4, tested in the El Paso study. The shaded gray area between the cylinder pressure trace and the suction and the discharge nozzle traces can be interpreted as the lost work required to pumping gas into and out of the cylinder against the valve resistance.

In 2001-2006, a Gas Machinery Research Council (GMRC) program examined valve stresses in order to predict valve life. A portion of this program was also sponsored by the Department of Energy through the Advanced Reciprocating Compressor Technology (ARC-T) program. Southwest Research Institute® (SwRI) engineers tested a series of valves at the GMRC Reciprocating Compressor Test Facility (RCTF) and the Hoerbiger valve slapper facility. This program was initiated because of the need for improving analysis tools in valve application engineering (Harris et al., 2003). Figure 2 shows the test setup at the Hoerbiger valve slapper facility. The program provided a limited set of data and yielded insight as to the effort required for future research. The research showed the need to validate a dynamic model of valve motion against actual test data. This research program provided a starting point for determining valve stress and modeling the valve's physical behavior.



Figure 2: Previous GMRC Valve Testing at Hoerbiger Valve Slapper Facility

Beyond the current valve designs, a better tool is needed to predict valve life based on compressor operating profile, geometry, material, and valve type. This paper describes results from recent research, which aimed to develop such a tool for valve

behavior and performance. This program can enhance the understanding of valve motion and the consequent stresses created by the valve's operating behavior. Namely, through the integration of experimentally validated FE analysis of transient plate stresses, a probabilistic valve plate motion model, based on real measured field data and accurate plate material properties, that is a predictive tool for reciprocating compressor valve plate life, can be developed. In combination with performance predictions, the predictive tool supports enhanced applications engineering for reciprocating compressor valves.

RECIPROCATING COMPRESSOR VALVE RESEARCH PROGRAM

The objective of this research was to better understand the factors affecting reciprocating compressor valve performance. In meeting this objective, the research aimed to develop a tool for predicting reciprocating compressor performance together with valve plate life. Valve life is considered to be a function of the plate cyclic 3-D kinematics and material properties. The program investigated these two fundamental aspects of reciprocating compressor valves in developing a method to predict valve life. The benefit of the research is primarily to increase compressor efficiency and reduce downtime by allowing the user to optimize machine performance and valve life for a desired operating profile and valve material.

The components of the reciprocating valve program are outlined in Figure 3. In order to model the motion of a valve plate and the compressor performance, the compressor geometry, operating conditions, and valve parameters must be known. Although these parameters dominate the requirements for predicting valve motion and compressor performance, the flow resistance and pulsations in the piping are contributory factors. The influence of these conditions should be evaluated by measuring the motion of the plate under varied operating conditions (*Program Element 1*). The results of the first round of Program Element 1 testing will be discussed briefly for one set of operating conditions. The results provided an average impact velocity, angle, and location for the opening and closing events. Subsequent research examined other valve designs and operating conditions (pressure ratio, speed, etc.). Characterizing the plate motion in three dimensions significantly differs from one-dimensional models of reciprocating compressor valve motion that the state of the art currently offers. Most of these one-dimensional models assume the plate to lift off the seat and move towards the guard

without any angularity to its movement. In reality, the plate moves toward the guard non-uniformly, with a significant level of angularity. The results of the research presented in this paper clearly show that the assumption of purely translatory motion of the plate is rarely valid. The precise motion of the plate is

not yet sufficiently understood in order to use angular motion in deterministic valve motion predictions. This research aims to provide a more detailed understanding of the plate movement, in translation from the seat to the guard, with realistic angularity of the plate.

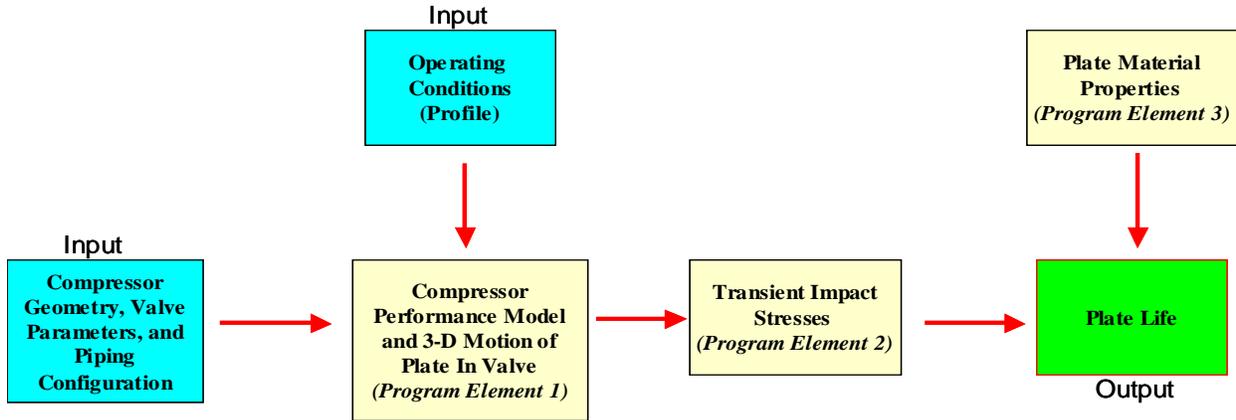


Figure 3: Roadmap for Reciprocating Compressor Valve Research

The 3-D motion of the plate can be used as input to an FE model that predicts plate transient impact stress as a function of impact velocity, angle of impact, and location (*Program Element 2*). However, the FE model must be validated against real data in order to calibrate and verify the model. To validate the model, controlled single impact tests were completed using a burst-membrane shock-tube. These tests provided useful characterizations of the kinematic behavior of the plate. The single impact tests were recorded to determine plate impact velocity, angle, and location. In addition, strain gauges provided strain measurements on the plate that correlated with the plate position recorded by displacement probes. Using the results from the single impact testing, the FE model was validated. The results of this program element will be discussed in detail.

is linking the realistic physical behavior of the valve plate to a validated stress model. Obtaining useable results from compressor test data to validate the model can be challenging because of the high frequency of impacts and the complex non-uniform motion of the plate. To understand the plate kinematics and validate the model, single impact testing was performed using a burst-membrane shock-tube. This testing allowed a realistic single impact event to be analyzed in detail without additional complicating valve motion characteristic of a typical reciprocating compressor.

Finally, a materials analysis of the plate material can be used in combination with a predictive model of plate stress to predict valve plate life (*Program Element 3*). The materials analysis is currently being conducted on PEEK material at various temperatures to characterize the fatigue behavior of PEEK. The results show conservative agreement with the manufacturer data. The fatigue testing will generate stress versus life data (S-N curves) that can be tied to model estimations of plate impact stress to predict plate life.



Figure 4: Burst-Membrane Shock-Tube

A 12-inch diameter burst-membrane shock-tube was constructed, as shown in Figure 4. A typical

DEVELOPMENT OF MODEL TO PREDICT VALVE IMPACT STRESSES

One critical aspect of predicting valve plate life

reciprocating compressor valve was mounted 4.0 meters downstream of the shock-tube. The valve was instrumented with optical position probes (in order to measure displacement of the valve plate) and strain gauges (in order to measure strain on the plate). The instrumented valve is shown in Figure 5. Three precision strain gauges (manufactured by Micro-Measurements with 120-ohm resistance) were mounted on the valve plate, which was affixed with reflective coating to optimize the available light for the optical probe measurement. The valve plate is shown in Figure 6. The high-speed optical probes were located on the outer diameter of the valve. This test setup provided detailed three-dimensional motion data and plate strain results.



Figure 5: Instrumented Valve Fixture



Figure 6: Valve Plate with Reflective Coating and Mounted Strain Gauges

The burst-membrane shock-tube testing was triggered with a plastic membrane and nichrome heat

wire mounted to the membrane surface. Once the membrane burst, a normal shock traveled downstream and hit the valve assembly. The valve test fixture measured the movement of the valve plate as it impacted the guard and bounced multiple times after the shock. No springs were used in the valve in order to understand the plate motion completely without the influence of the spring elements. For each test, the data acquisition period began with the membrane burst. The data acquisition rate was approximately 10 kHz on six separate channels, which allowed sufficient sampling resolution of the three high-speed optical position probes and the three strain gauges.

Four single impact tests were performed to capture a range of impact locations, angles, and velocities. The single impact profile matched previous plate profiles obtained in the Hoerbiger valve slapper. Figure 7 compares the two motion profiles. As the figure shows, the motion profile from single impact testing correlated with the multiple impacts recorded in the valve slapper. The three optical probe sensor measurements were used to determine how the plate impacted the guard, its subsequent motion, and the impact velocity. Figure 8 shows the plate motion plot generated from the three optical position probes. The motion of the plate is not uniform and causes the plate to impact at an angle rather than flat. (However, valve springs tend to reduce the angularity of the impact.) The plate motion data also indicates that the plate bounces after the initial impact. In the first impact, the plate hits at the 9 o'clock position, followed by a more flat impact at the 12 o'clock and 3 o'clock positions, and then, lastly, at the 6 o'clock position. In the repeated hits after the initial impact and the subsequent "ringing" effect, different areas of the plate show varied amounts of movement, which confirms the plate's angular movement.

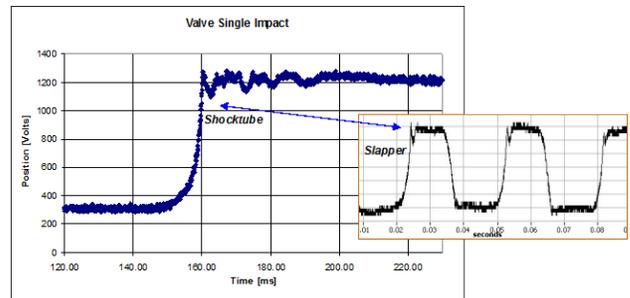


Figure 7: Comparison of Plate Motion Profile in Single Impact Shock-Tube Test and Hoerbiger Valve Slapper

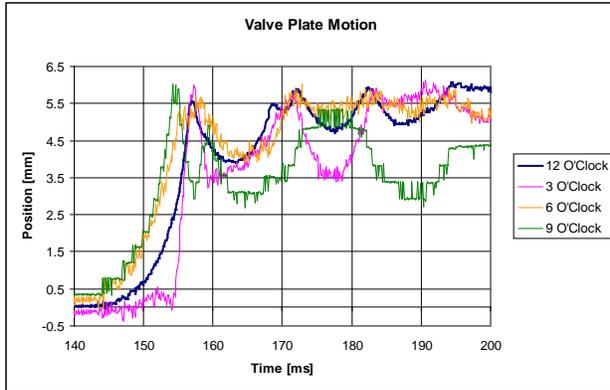


Figure 8: Valve Motion Recorded by Optical Position Probes, with Probe Coordinate Transformation

Figure 9 shows that the time traces from the strain gauges were consistent with the plate motion profile. The plate strain is at a maximum at the first impact at approximately $1,150 \mu\epsilon$ peak-to-peak. The second and third bounce of the valve plate show significantly less strain and tend to follow a logarithmic decay in strain over time. This result is significant, because it means that the primary impact causes the greatest strain on the valve plate, and the resulting impacts are considerably weaker. Figure 10 compares the plate position to the valve strain to reveal the good correlation between the measured strain values and the plate displacement. The plot also shows the ringing phenomenon after the plate's discrete impact points. The results from the shock-tube testing demonstrated a maximum plate impact velocity of 3.6 m/s , an impact location at 245° , and an impact angle of approximately 5.6° . Measurement uncertainties for velocity, impact angle and stress were around 20%, while the uncertainty for the stress measurement was slightly less at approximately 15%.

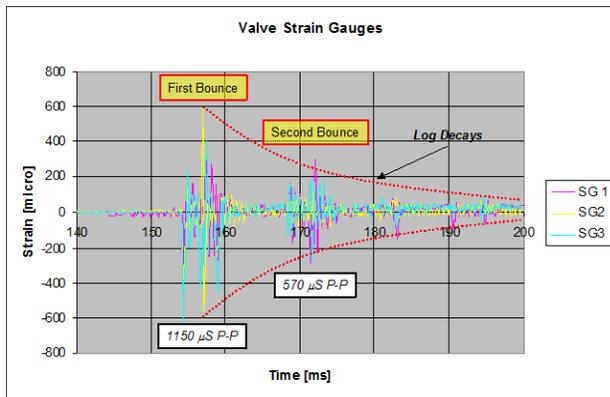


Figure 9: Corresponding Valve Strain Measured by Strain Gauges during Simple Impact Testing

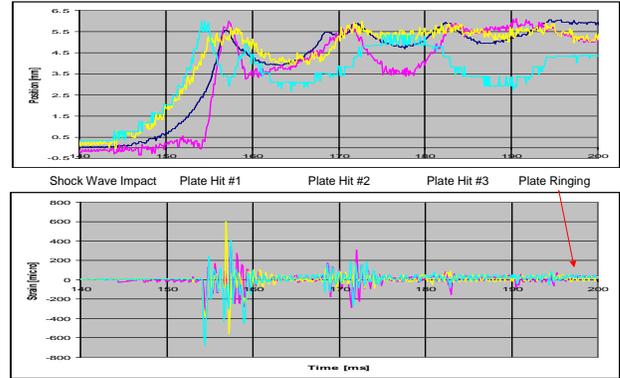


Figure 10: Comparison of Measured Valve Position and Strain during Single Impact Test

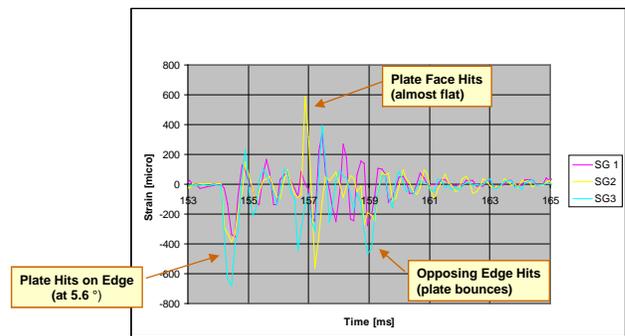


Figure 11: Expanded Valve Strain Measurements for Initial Plate "Bounce"

An enhanced view of the initial impact (i.e., the first bounce) of the valve plate provides a detailed explanation of the strain generated by a single impact event. Figure 11 shows the strain of the valve plate at four locations during the first hit. From this strain plot, it is evident that the plate hits on its edge first at an angle of 5.6° , generating a peak-to-peak strain of approximately $950 \mu\epsilon$. The plate then hits almost flat with a maximum peak-to-peak strain of $1140 \mu\epsilon$. Lastly, the opposing edge strikes the guard at a less significant level ($570 \mu\epsilon$ P-P). These values of strain show the initial edge impact, and the latter full plate hit generate the maximum strain in the valve plate. After the first impact events, the valve plate continues to bounce against the guard, but with a considerably reduced level of strain (and stress).

Thus, the single impact testing yielded a characterization of the valve plate kinematic behavior versus strain. The test results can be used to validate an FE model developed to simulate a single impact event for the valve plate. The FE model inputs were the impact velocity, angle, and location of the valve plate. To model the dynamic plate behavior, ANSYS was used to perform a transient stress calculation (typical valve plate geometry using 2438 elements).

Model predictions for transient stress could be compared directly to the calculated stress based on measured strain values. Figure 12 shows an example of the FE model transient stress calculation. Model predictions of the plate movement could also be compared to the plate position plot. Table 1 highlights the good agreement between the FE model and the experimental data. The model predicted stress was slightly less than the measured stress in all cases, but within the uncertainty of the shock-tube test.

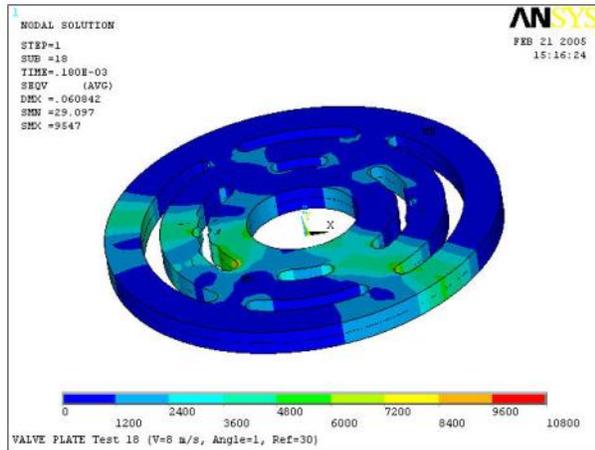


Figure 12: FE Model of Valve Plate after Plate Single Impact and Resulting Stress Wave Propagation

Table 1: Summary of Results Comparing FE Model Performance to Measured Stress Data

Test No.	#25	#31	#45	#49
Velocity (m/s)	3.2	3.6	2.5	2.3
Impact Angle	3.8°	5.6°	5.3°	5.5°
Location	74°	245°	251°	247°
Measured Stress (MPa) (Closest SG, E = 4.3E4 kPa)	38	41	26	27
FE Model Stress (MPa) (Closest SG, E = 4.3E4 kPa)	33	36	24	23
FE Model Deviation	15%	14%	8%	17%
<i>FE Model Deviation is within stress measurement uncertainty (U_{st}=20%)</i>				

To predict the stress levels at other impact angles and velocities, the FE model was used in a parametric study to determine the relationship between the plate kinematic behavior and transient stress levels. For a range of impact angles, velocities, and locations, the parametric study identified the highest stress location for a particular set of input values. The quarter symmetry about the plate allowed a detailed

parametric evaluation of the plate to be performed on a single quarter section. Maximum and minimum stress levels expected at particular locations were identified for specific impact angles and velocities. An example of the results obtained at an impact location of 30 degrees is shown in Figure 13. The figure shows the increase in peak-to-peak stress as velocity increases. At an increased impact angle, the stress level increases more rapidly as velocity increases.

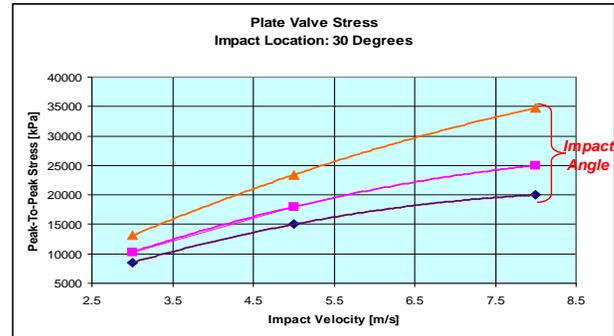


Figure 13: Parametric Study Results Using FE Model for Impact Plate Location of 30 Degrees

Thus, the FE model will be used to predict valve life based on material stress-life properties and a characterization of the valve motion over a range of operating conditions. The testing proved to be worthwhile in understanding the kinematic behavior of the valve plate and the stress created by the differential pressure force across the plate. The single impact testing also provided the following conclusions about the kinematic motion of the plate:

- The valve plates were seen to always hit at an angle.
- The plate usually “bounces” at least one more time after the initial impact, but the subsequent impacts are softer.
- The highest stress events within each impact occur when the initial edge of the plate hits and the full plate hits, which is followed by the opposing edge hit.
- The initial edge and full plate hit generate the highest stresses (evident in Figure 11), and both of these hits create similar levels of stress (within 20% of magnitude).
- The highest stress levels decay quickly, but the plate continues to “ring” after impact, creating ongoing dynamic low stress.

PLATE MOTION ANALYSIS

In order to effectively use the transient stress predictions of the FE model, the 3-D plate motion must be understood for a range of operating

conditions and valve/piston designs. Thus, another critical element of the reciprocating compressor valve program is the study of the plate motion in reciprocating compressor machines (Program Element 1, as shown in Figure 3). This element of the program provides the data needed to characterize the three-dimensional motion of the valve plate. Once the characterization is complete for a range of operating conditions and design parameters, a probabilistic method can be developed to provide the necessary inputs (impact velocity, angle, and location) to the transient stress model.

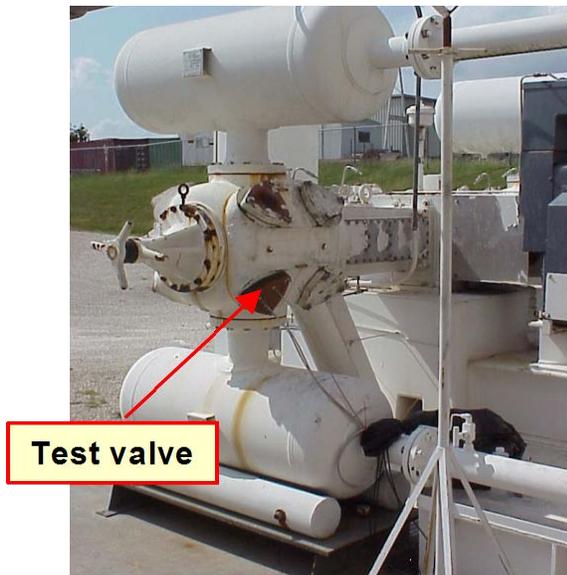
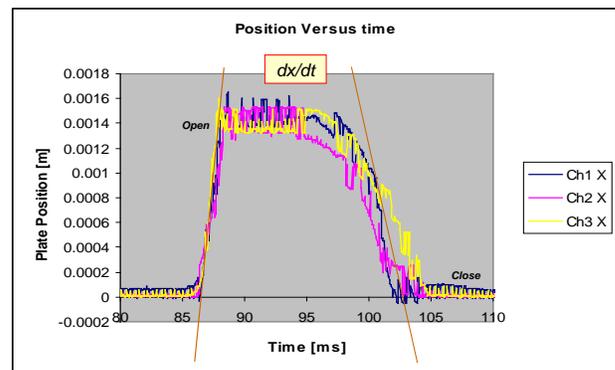


Figure 14: Ariel Reciprocating Compressor Used in Measuring Valve Motion

To study the valve plate motion, a series of tests were conducted at the SwRI Metering Research Facility using an Ariel 250 HP reciprocating compressor, shown in Figure 14. Three optical position probes were used to monitor the position of the valve plate. The optical position probes were mounted on the discharge valve (see Figure 15). The displacement data from the probes was then used to determine the plate velocity, angle of impact and impact location. An example of the calculated impact velocity determined from the optical position probe data is shown in Figure 16. The first round of testing measured the plate valve response for one particular set of springs at a speed of 900 RPM and a range of compression ratios. In the second round of testing, the valve spring stiffness was varied to determine the effect of spring stiffness on valve motion.



Figure 15: Ariel Reciprocating Compressor with Optical Position Probes Mounted on Valve



Impact Velocity: 1.53 m/s 1.29 m/s

Figure 16: Typical Position Probe Data Used to Calculate Impact Velocity on Ariel Compressor

Using the test data, a number of empirical relationships between operating conditions, geometry, and valve three-dimensional motion were developed. For example, one consistent empirical relationship is found between impact angle and plate velocity, as shown in Figure 17 and Figure 18. These figures show that opening and closing impact velocities depend on the impact angle of the plate. In both instances, the plate velocity increases for decreasing impact angle. In the second round of testing, the spring stiffness was increased in the discharge plate valve. Initial results of the second round of testing are shown in Figure 19, which compares the two values of spring stiffness to the impact velocity of the plate. The opening impact velocity is not affected by the change in spring stiffness, while the closing impact velocity increases significantly when the stiffness is increased. These results suggest that, in the case of the discharge valve, the pressure forces acting on the valve from the cylinder dominate the opening impact velocity.

The closing impact velocity is controlled by the spring forces, as shown by the significant increase in closing impact velocity when stiffer springs were used. If the springs have relatively low spring stiffness, the valve closes more softly.

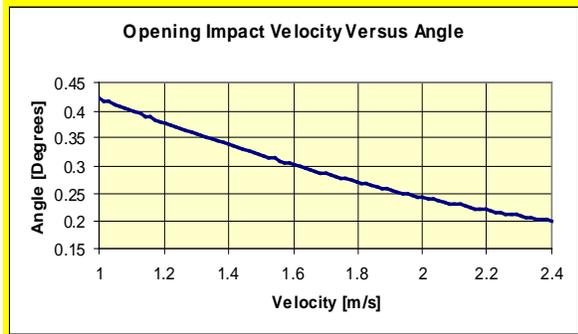


Figure 17: Correlation between Impact Angle and Opening Velocity for Valve Plate, Based on Displacement Probe Data

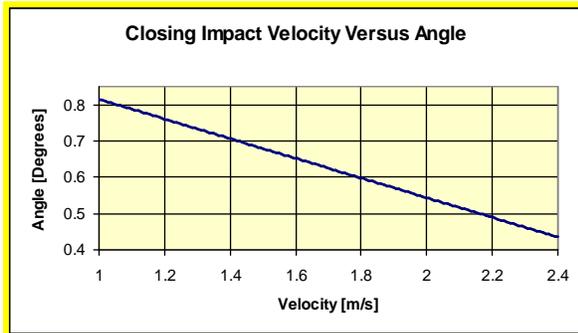


Figure 18: Correlation between Impact Angle and Closing Velocity for Valve Plate, Based on Displacement Probe Data

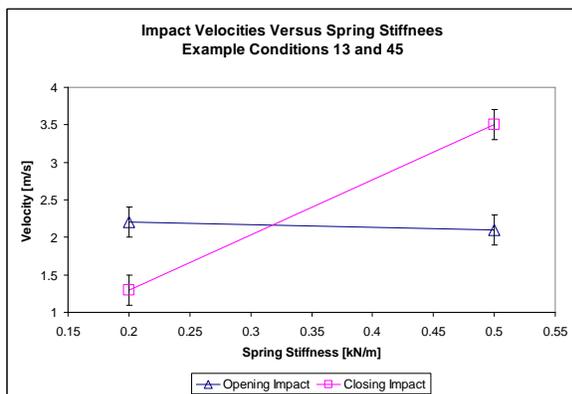


Figure 19: Variation in Spring Stiffness for Opening and Closing Impact Velocities.

After the second round of testing on the 250 HP reciprocating compressor, a final set of data was taken with a variable frequency drive installed on the compressor. The variable drive allowed the

compressor speed to be varied. Valve motion data for compressor speeds of 500, 600, 700, and 800 RPM and pressure ratios of 1.3 to 1.6 was recorded. The effect of operating speed on impact velocity and impact angle was assessed based on this data. It should be noted that speeds above 900 RPM were not permitted on the test machine. If the modeling tool developed from this research is to be used at higher operating speeds, re-calibration of some parameters may be in order.

MATERIALS ANALYSIS

In addition to understanding the three-dimensional valve motion and predicting the transient stress, a stress-life analysis of the valve plate material is being performed. Predictions of the transient stress model were converted into an estimation of valve life using customized S-N material curves. These curves were developed through fatigue life testing performed on PEEK material samples at SwRI's material laboratory to determine the number of cycles to failure at various stress levels.

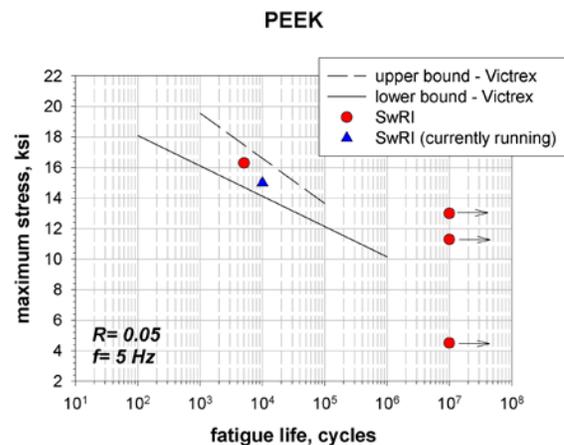


Figure 20: Experimental S-N Curves Developed Through Fatigue Testing

Fatigue testing of PEEK was performed at room temperature at stress levels of 4.5, 11.3, 13, and 16.3 KSI at a frequency of 5 Hz. The testing was consistent with manufacturer predictions, but also indicated that fatigue life is nearly infinite for very low stress levels. The experimentally determined S-N curve based on the testing is shown in Figure 20. Additional stress levels were tested at elevated temperatures to develop more S-N curves for PEEK (below and above the glass transition temperature). These tests were run at similar stress levels to determine the effect of temperature on valve plate life. The materials analysis determines the yield stress of typical plate valve materials based upon the number of level out cycles measured. The results are

combined with valve motion data and the FE model to estimate valve life using the plate valve life application tool developed through the research.

PLATE VALVE LIFE ANALYSIS TOOL

The FE model of plate valve stress and the material analysis were combined with the empirical relationships developed through the 3-D valve motion assessment in a plate valve life analysis (VLA) tool. The VLA allows the user to easily evaluate the effect of compressor performance parameters, valve geometry, design parameters, and valve operation on the effective life of the plate valve. A screen-shot of the application interface screen for the VLA is shown in Figure 21. An existing compressor performance simulation tool is used by the application to generate a one-dimensional plate motion profile based upon the compressor performance. The VLA is then called by the valve life program application to determine the valve impact velocities. The VLA automatically extracts the opening and closing impact velocities for each compressor valve location.

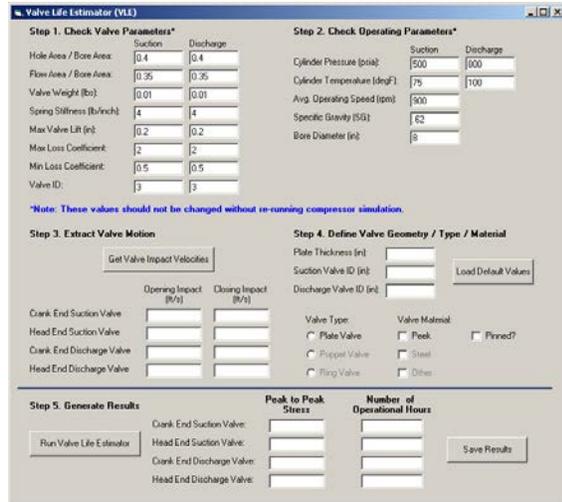


Figure 21: User Interface for Valve Life Analysis Tool

Once the impact velocities are determined based upon the specific operating conditions of the compressor and the valve geometry, the VLA calculates three plate bounces per impact velocity and two angular plate impact events per bounce. For one cycle of the compressor, the VLA determines 12 individual impact events for a particular valve location. Finally, the VLA formulates a 3-D model of the valve velocity and impact angle for each impact event. This model is the basis for the stress prediction using the FE model previously developed. The VLA tool determines peak-to-peak stress levels based upon the FE model.

Using the material properties for peek, stainless steel (SS316) or nylon, the VLA tool estimates valve life, using the experimentally developed S-N curves and the assumption of continuous operation of the plate valve. The VLA tool is particularly useful in that it can easily perform calculations of valve stress and valve life based upon varying parameters such as the valve lift, spring stiffness, or compressor speed. The application tool has the ability to compute compressor efficiency, which is a direct design trade-off to valve lift in traditional reciprocating compressor passive valve technology. The application will be further developed to serve as a valve analysis tool for the two remaining basic valve designs (ring valves and poppet valves).

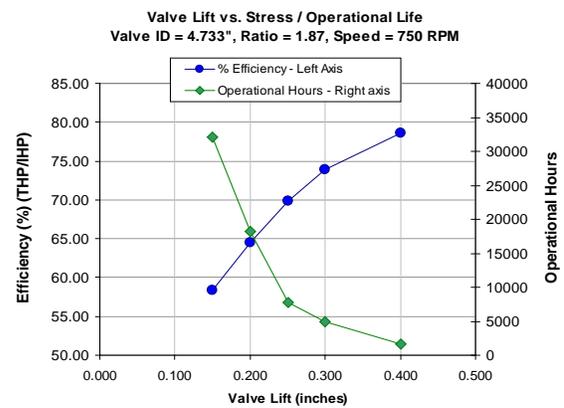


Figure 22: Valve Life Analysis Tool: Relationship between Valve Life and Efficiency versus Valve Lift

Though the plate valve life analysis model was developed based on experimental data and verified model predictions, the analysis tool itself must be verified through actual field measurements given a particular operating environment, valve material, and flow area. Initial testing with the beta version of the model indicates that the VLA tool predicts trends that are consistent with existing relationships. For example, Figure 22 shows the relationship of plate life and valve efficiency versus valve lift. As lift increases, valve efficiency increases, but plate life declines rapidly.

As the 3-D valve motion model is improved through field testing of different valve types, the VLA application can be updated or calibrated to suit a particular valve design. The intent of the research is to develop an application tool that can be used by operating companies to determine the optimal valve performance and compressor operation, through a study of the net effect of design tradeoffs and compressor operational changes. The research does not aim to predict the valve life in terms of absolute accuracy.

RECENT RESEARCH

After the development of the original valve life analysis tool through the DOE sponsored program Advanced Reciprocating Compressor Technology (ARCT), SwRI continued to investigate changes to traditional passive valve technology through testing in its valve test facilities and development of new surface coatings through its materials engineering groups. These recent research findings are summarized below.

- Contoured flow paths for lower DP – SwRI developed plate valve design with contoured flow channels to reduce flow losses evident through abrupt inlet/ outlet channels (square-edged) and increase flow area. Plate valves with rounded channels were designed and fabricated in a rapid prototype machine and tested in a closed-loop air facility. Constant flow tests were performed in a valve test rig with the valve in a fixed open position. These tests were used to measure effective flow area and constant pressure drop (non-pulsating flow, full open position). Tests showed an improvement of 20-30%, compared to traditional plate valve designs.
- Anti-stiction coating – Oleophobic coatings were investigated as a means of reducing stiction. Stiction often leads to higher impact velocities because of the valve plate's tendency to delay opening or closing due to stiction with the guard or seat. An oleophobic coating was applied, drop tested, and compared to a typical valve coating surface. Significant qualitative valve impact velocity reductions were recorded.
- Optimized springs – Springs are typically sized for a single operating condition and can be the dominant factor in causing valve failures. Advanced materials and non-linear springs can be considered to extend the operating range and further optimize valve designs. An FEA model was developed to study spring behavior.
- Semi-active valve – SwRI developed and tested a new semi-active valve design. This design was later patented and tested for a period of 18 months at a compressor station on a typical reciprocating compressor. The program demonstrated utilized the premise that a controlled valve impact through a “braking mechanism” provided by electromagnets can be used to reduce valve stress and prolong valve life. The new design successfully controlled impact velocity through electromagnetic force to counter-act

spring force and extended valve life significantly (from a matter of days to many months). This advancement effectively broke the interdependency between pressure drop or efficiency (increased flow area/ lift) and valve life such that these two crucial parameters were no longer design trade-offs. Once valve life can be controlled, the efficiency can be optimized through other valve advances (increased flow area, increased life) without limiting valve life as an expense.

SUMMARY

The reciprocating compressor valve research aims to improve compressor efficiency and reduce downtime by enhancing valve performance. Within the Valve Life Analysis modeling and optimization tool, a dynamic FE model has been developed and validated against single impact test data for plate transient stress analysis. Combining these stresses and valve motion predictions with material stress-life characteristics provides a prediction of valve plate life in terms of operating hours. The data gathered through the analysis of valve motion and materials testing were combined in a working application tool for valve users. The prediction capability of the plate valve life tool should enable the reciprocating compressor user to tune the machine performance to reduce valve stress and prolong valve. The tool will allow users to balance valve life and performance to meet a particular operation/ business need for the compressor. This application is primarily useful in weighing the effects of valve performance characteristics in terms of valve life and in determining foreseeable benefits of changing the valve springs, pre-load or lift. Lastly, the more recent research has shown that valve efficiency and life can be aided by advances in plate valve contoured flow paths, specialized coatings, and most importantly, electromagnetic control of the valve impact velocity to reduce maximum stresses. The findings of this work also suggest that valve advances may be made to beneficially aid both valve operational life and efficiency by eliminating the traditional passive valve inverse dependency between life and efficiency.

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